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INPUT-OUTPUT AND HYBRID LCA

Towards a triple bottom-line sustainability assessment of the U.S. construction industry

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Abstract
Purpose The construction industry has considerable impacts on the environment, economy, and society. Although quantifying and analyzing the sustainability implications of the built environment is of great importance, it has not been studied sufficiently. Therefore, the overarching goal of this study is to quantify the overall environmental, economic, and social impacts of the U.S. construction sectors using an economic input–output-based sustainability assessment framework.
Methods In this research, the commodity-by-industry supply and use tables published by the U.S. Bureau of Economic Analysis, as part of the International System of National Accounts, are merged with a range of environmental, economic, and social metrics to develop a comprehensive sustainability assessment framework for the U.S. construction industry. After determining these sustainability assessment metrics, the direct and indirect sustainability impacts of U.S construction sectors have been analyzed from a triple bottom-line perspective.
Results When analyzing the total sustainability impacts by each construction sector, "Residential Permanent Single and Multi-Family Structures" and "Other Non-residential Structures" are found to have the highest environmental, economic, and social impacts in comparison with other construction sectors. The analysis results also show that indirect suppliers of construction sectors have the largest sustainability impacts compared with on-site activities. For example, for all U.S. construction sectors, on-site construction processes are found to be responsible for less than 5 % of total water consumption, whereas about 95 % of total water use can be attributed to indirect suppliers. In addition, Scope 3 emissions are responsible for the highest carbon emissions compared with Scopes 1 and 2. Therefore, using narrowly defined system boundaries by ignoring supply chain-related impacts can result in underestimation of triple bottom-line sustainability impacts of the U.S. construction industry.
Conclusions Life cycle assessment (LCA) studies that consider all dimensions of sustainability impacts of civil infrastructures are still limited, and the current research is an important attempt to analyze the triple bottom-line sustainability impacts of the U.S. construction sectors in a holistic way. We believe that this comprehensive sustainability assessment model will complement previous LCA studies on resource consumption of U.S. construction sectors by evaluating them not only from environmental standpoint, but also from economic and social perspectives.

Keywords Economic input–output analysis · Life cycle assessment · Sustainability assessment · Triple bottom line · U.S. construction industry

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1 Introduction

1.1 The U.S. built environment

The construction industry consists primarily of establishments related to constructing, renovating, and demolishing buildings and other engineering structures. The construction industry includes contractors in commercial, residential, highway, heavy industrial, and municipal utility construction (U.S. EPA 2010). In the United States, the construction sectors accounted for $611 billion, or 4.4 % of the gross domestic product (GDP), more than many industries, including information, arts and entertainment, utilities,

agriculture, and mining (BEA 2010). Additionally, construction sectors are one of the main contributors to the depletion of natural capital, and a significant source of environmental pollutions, such as air, water, and soil, solid waste generation, land use, toxic wastes, health hazards, and global climate change. For example, in the U.S., 80 % of all resources by mass are employed in construction, renovation, and retrofit of buildings and infrastructures (Gradel and Allenby 2009). Buildings and infrastructure also account for approximately 30 % of the raw materials and 25 % of the water used annually in the U.S. In addition, construction projects annually generate 164,000 million tons of waste and demolition debris, which accounts for about 30 % of the content in landfills (NRC 2009).

1.2 Environmental life cycle assessment

Due to the fact that the built environment has significant impacts on the environment, it is necessary for the construction industry stakeholders to address the issues related to sustainable construction. Today, many construction companies have given a substantial importance to sustainability and resource conservation, and therefore the environmental life cycle assessment (LCA) of construction activities have become a subject of considerable interest globally (Sharrard et al. 2005).

LCA was introduced in the early 1990s as a hands-on tool to evaluate the potential environmental interventions by providing complimentary insights, apart from current regulatory practices and to help reduce the overall environmental impacts (Rebitzer et al. 2004). LCA is a widely used approach to assess the potential environmental impacts and resources used throughout a product's life cycle, including raw material acquisition, production, use, and end-of-life phases (Finnveden et al. 2009). The most significant strength of this approach is that it considers the whole product life cycle so as to avoid problems associated with defining a limited scope.

LCA-based decision support tools have also been developed for analyzing the environmental implications of buildings and building materials both in the Europe and United States (Haapio and Viitaniemi 2008). To give a few examples, ENVEST was developed in UK to quantify the environmental impacts of buildings considering materials utilized in construction and maintenance (Tatari and Kucukvar 2012a). In addition to that, the Building Environmental Assessment Tool, which was developed by the Danish Building and Urban Research Institute, provides a LCA-based inventory and database for the life cycle assessment of building products, as well (Forsberg and Malmborg 2004). ATHENA, which estimates the life cycle environmental impacts of construction materials and building systems, was developed by the Athena Sustainability Institute in North America as a decision support tool for buildings (Seo and Hwang 2001). The U.S. National Institute of Standards and Technology has also developed Buildings for Environmental and Economic Software to select environmental and economically balanced building materials for commercial and residential buildings (Lippiat 2007). The National Renewable Energy Laboratory (NREL) Life Cycle Inventory database which was developed by the Athena Institute and NREL provides some data on building material production and transportation; however, it does not provide any information regarding construction processes (NRL 2012).

1.3 Applications of the EIO-LCA to construction industry

The aforementioned LCA-based environmental decision support models analyze the life cycle environmental impacts of some building materials; however, they are not able to consider the indirect impacts of construction sectors, including non-residential heavy civil infrastructures. In this regard, economic input–output-based life cycle assessment (EIO-LCA) has been utilized extensively to analyze the environmental impact of the construction industry. The EIO-LCA model augments the environmental impact data with the economic input–output tables to form a comprehensive system boundary and is widely used for quantifying the environmental pressures of products or processes by tracing the entire supply chain (Hendrickson et al. 2005; Joshi 2000; Lenzen et al. 2003).

Several interesting applications of the EIO analysis are found in the literature for the environmental analysis of buildings and other engineering structures. For instance, Hendrickson and Horvath (2000) estimated the major commodity and service inputs, resource requirements, environmental emissions, and wastes for four major U.S. construction sectors, including highway, bridge, and other horizontal construction, industrial facilities, and commercial and office buildings, residential one-unit buildings, and other constructions such as towers, water, sewer and irrigation systems, railroads, etc. Hendrickson and Horvath quantified all direct and indirect material, energy, and service inputs for these construction sectors using the EIO-LCA model. In addition, Ochoa et al. (2002) estimated the total resource, fossil energy, greenhouse gas emissions (GHG), hazardous waste generation, and toxic releases into air for the construction, use, and demolition phases of the U.S. residential buildings by using the EIO-LCA model, which considered the interaction among 480 sectors in the United States. Junnila and Horvath (2003) analyzed the life cycle energy use and atmospheric emissions of newly constructed European and U.S. office buildings from materials production through construction, use, and maintenance to end-of-life treatment using the process-based LCA (P-LCA) and EIO-LCA methodologies.

In another study, Bilec et al. (2006) developed a comprehensive hybrid LCA model combining both the P-LCA and EIO-LCA methodologies to quantify the atmospheric emissions related to construction of a precast concrete parking garage. In addition, Sharrard et al. (2005) constructed an input–output-based hybrid LCA methodology to estimate the environmental impacts of construction processes, comprehensively. On the other hand, Tatari and Kucukvar (2012b) brought a different approach by using an ecologically based LCA tool to quantify the cumulative ecological resource consumptions of the buildings and civil infrastructures for the first time. Tatari and Kucukvar holistically evaluated 13 U.S. construction sectors by using several key sustainability assessment metrics, such as resource intensity, efficiency ratio, renewability ratio, and loading ratio.

1.4 Motivation and organization of the research

The previous LCA studies have successfully analyzed the environmental impacts of buildings and other civil infrastructures from a system-wide perspective. In addition to the environment, sustainable construction should also include the economic and social aspects. Hence, the EIO methodology could be expanded to estimate the environmental, as well as the economic and social impacts of different U.S. construction sectors, including residential and non-residential structures. The current study aims to fill this important research gap and account for the total sustainability impacts of the construction industry, including its supply chain. This analysis is achieved by using several sustainability metrics augmented with the U.S. economic input–output tables to reach to better insights regarding a triple bottom-line sustainability performance of the nation's construction sectors.

The rest of the paper is structured as follows. First, a comprehensive economic input–output methodology has been presented. Second, sustainability indicators such as environmental, economic, and social are briefly defined, and their corresponding data sources are presented. Next, sustainability impacts of the U.S. construction industry including residential and non-residential construction sectors have been presented with details. Finally, the findings are discussed, and the limitations are pointed out.

2 Methodology

In this research, we utilized the EIO-based sustainability accounting approach to analyze the sustainability of the U.S. construction sectors from a holistic perspective. The EIO analysis is a well-established model, which was theorized and developed by Wassily Leontief in 1970s, based on his earlier works in the late 1930s, for which he received the Nobel Prize (Leontief 1936). In its original form, the EIO analysis is a top-down technique, which consists primarily of financial flows and interdependencies between different sectors that make up the economic structure of a nation (Suh et al. 2004). In the literature, this methodology has been extensively used to analyze a wide range of policy issues in environmental, economic, and social areas, and several researchers comprehensively analyzed the sustainability impacts of products, infrastructures, energy systems, private sectors, international trade, and household demand (Huang et al. 2009a; Huppes et al. 2008; Lenzen et al. 2003; Suh and Lippiat 2012; Tatari et al. 2012; Weber and Matthews 2007; Wiedmann et al. 2011).

In this study, the supply and use tables published by the U.S. Bureau of Economic Analysis (BEA 2002), as part of the International System of National Accounts, are merged with a range of environmental, economic, and social sustainability metrics to develop a comprehensive sustainability assessment framework for the U.S. construction industry. The commodity-industry format is utilized since the basic input–output model presents the financial flows between industrial sectors without distinguishing between primary and secondary products. However, using commodity-industry format, it is possible to account for the fact that an industry can produce more than one commodity, such as secondary products and by-products (Wachsmann et al. 2009). Especially, the Eurostat manual provides a comprehensive and detailed discussion on the use of this format in the EIO models (Eurostat 2008).

In this approach, the Use matrix, which is usually denoted as U, provides information on the consumption of commodities by industries or by final demand categories, such as households, government, investment, or export. As an element of U, u_{ij} denotes the value of commodity purchase of commodity i by industry j and x_j represents the total output of industry j, including imports. Therefore, b_{ij} is the amount of commodity i required for producing one-dollar output of industry j. By using the total industrial output of industry j, the technical coefficient matrix B can be written as (Miller and Blair 2009):

$$B = \left[b_{ij}\right] = \left[\frac{u_{ij}}{x_j}\right] \tag{1}$$

In addition to the Use matrix, the Make matrix, which is usually denoted as called as V, provides detailed information on production of commodities by industries. In the make table, each row represents the production of commodities by different industries. As an element of the Make matrix, v_{ji} is the value of the output of commodity i by industry j and q_i represents the total output of commodity i. Hence, d_{ji} represents the fraction of total commodity i output which is

produced by industries both as main product as well as by-product. Using the total output of commodity i, the industry-based technology coefficient matrix D can be written as (Miller and Blair 2009):

$$D = [d_{ji}] = \left[\frac{v_{ji}}{q_i}\right] \tag{2}$$

After defining B and D matrices, an industry-by-industry input–output model can be formulated as follows (Miller and Blair 2009):

$$x = \left[(I - DB)^{-1}\right]f \tag{3}$$

where x represents the total industry output vector, I refers to the identity matrix, and f is the total final demand vector for industries. In addition, B is the input requirements for products per unit of output of an industry matrix, and D is sometimes called as market-share matrix. Also, the term $[(I-DB)^{-1}]$ represents the total requirement matrix, which is also known as the Leontief inverse, and DB is the direct requirement matrix, which is represented by A matrix in the Leontief input–output model (Leontief 1970). For more detailed information on transformation of the supply and use tables into a symmetric industry-by-industry model, please see the reference reports prepared by the Eurostat and the United Nations (Eurostat 2008; UN 1999).

After an industry-by-industry input–output framework has been established, total sustainability impacts (direct and indirect) can easily be calculated by multiplying the final demand of a sector with the multiplier matrix. Then, a vector of total sustainability impacts can be formulated as follows:

$$r = E_{\text{dir}}x = E_{\text{dir}}\left[(I - DB)^{-1}\right]f \tag{4}$$

where r denotes the total-impacts vector that represents overall sustainability impacts per unit of final demand, and E_{dir} represents a diagonal matrix, which consists of the direct environmental, economic, or social impact values per dollar of output for each industrial sector. Each element of this diagonal matrix is simply calculated by dividing the total direct sectoral impact (e.g., water consumption, GHG emissions, income) with total economic output of that sector. In addition, the product of E_{dir} and the bracketed term $[(I-DB)^{-1}]$ represents the multiplier matrix.

Using a power series expansion of the Leontief inverse, it is also possible to account for the impacts of direct and indirect suppliers on environmental, economic, and social impact categories. Equation 5 presents the mathematical framework of the power series approximation of the Leontief inverse that is applied in our research (Hendrickson et al. 2005):

$$x = [(\underbrace{I}_{\text{L1}} + \underbrace{(DB)}_{\text{L2}} + \underbrace{(DB)^2 + (DB)^3 + \cdots}_{\text{L3 and higher}})]f \tag{5}$$

Using this power series approximation, the results are presented in three different layers to account for the contribution of high-order suppliers to each sustainability indicator. In this analysis, Layer 1 (L1) represents each construction sector itself, which is contributing with on-site activities through direct use of energy or water, as well as direct economic and social impacts. Layer 2 (L2) accounts for contributions from all direct suppliers to U.S. constructions sectors. Finally, Layer 3 (L3) and higher represent the suppliers of the suppliers and other high-order suppliers in the U.S. economy.

3 Sustainability assessment indicators

We utilized the input–output analysis to build a comprehensive sustainability assessment framework of the U.S. economy using numerous environmental, economic, and social indicators. These sustainability indicators are considered as multipliers and will be then used to analyze each of the U.S. construction sectors. After determining these sustainability assessment metrics, we quantify the direct and indirect sustainability impacts of the U.S construction industry from a triple bottom-line perspective.

3.1 Economic indicators

Firstly, gross operating surplus (GOS), contribution to GDP, and import are selected as key economic indicators and are presented in terms of millions of dollars ($M). The values of these economic indicators are obtained from the U.S. input–output tables (BEA 2002). Although it was not used for a sustainability analysis of construction sectors, these indicators were merged with the EIO analysis before to provide a macro-level sustainability accounting framework (Foran et al. 2005; Wiedmann and Lenzen 2008). These economic indicators of sustainability are defined as follows:

- GOS is obtained as a residual for most industries after subtracting total intermediate inputs, compensation of employees, and taxes from total industry output (Eurostat 2008). GOS is a positive economic indicator since it represents the capital available to sectors, which allow them to repay their creditors, to pay taxes, and to finance their investments.
- GDP is used as another useful economic indicator. GDP represents the market value of goods and services produced within the country in a given period of time. GDP is a positive economic indicator that

monitors the health of a nation's economy and includes compensation of employees, gross operating surplus, and net taxes on production and imports (Lenzen and Dey 2002). This positive economic indicator is the direct and indirect contribution of one sector to GDP.

- Imports represent the value of goods and services purchased from foreign countries to produce domestic commodities by industries (Wiedmann et al. 2009) Imports can be considered as a negative indicator due to the fact that an excess of imports means an increase in the current deficit through the flow of money out of the country. This economic indicator accounts for the direct and indirect contributions of one sector to foreign purchases.

3.2 Social indicators

Social indicators of sustainability are also critical since they are considered an integral part of the life cycle sustainability assessment framework that analyzes environmental, economic, and social dimensions of sustainable development (Guinée et al. 2011; Klöpffer 2008; Zamagni 2012). In this study, three social indicators such as income (\$M), taxes (\$M), and work-related injuries (number of employee) are selected as prominent social indicators and obtained from federally available public data sources. These social sustainability indicators are defined as follows:

- Income is considered an important social indicator since it contributes to the social welfare of households and represents the compensation of employees, including wages and salaries (Wiedmann et al. 2009). The income generated by each industrial sector is obtained from the U.S. input–output tables (BEA 2002).
- Taxes are chosen in this study as a positive sustainability indicator since collected taxes will be used for supporting the national health and education systems, public transportation, highways, and other civil infrastructures (Foran et al. 2005). Taxes are referred to as government revenue, which includes the taxes on production and imports. The data source for taxes generated by each sector is the U.S. input–output tables (BEA 2002).
- The U.S. construction industry accounts for the largest share of work-related injuries and illnesses, and results in loses in wage and productivity of households (Waehrer et al. 2007). Hence, injury is a critical indicator of social sustainability that has a significant impact on the quality of life. This negative indicator represents the total number of non-fatal injuries at industrial facilities. The data including the number of total work place injuries are gathered from the U.S. Bureau of Labor Statistics (BLS) to investigate the contributions of the U.S. construction sectors to work-related injuries (BLS 2002). The BLS provides publicly available data, which present the rate of non-fatal injuries per 100 equivalent full-time employees. To calculate the total number of direct injuries for each U.S. sector, the total number of full-time employees is then multiplied with corresponding incidence rates per 100 full-time workers.

3.3 Environmental indicators

The United Nations Environment Program (UNEP) has recently released emerging environmental concerns and ranked water scarcity, global climate change, and energy resource depletion among the most important emerging issues related to the global environment (UNEP 2012). With the aim of analyzing the direct and indirect contributions of the U.S. construction sectors to the aforementioned major themes of the global environment, water, carbon, and energy footprint categories have been presented in our analysis. The diagonal environmental impact matrixes including the value of these environmental indicators per \$M output of each industrial sector is obtained from the EIO-LCA model, which was developed by the Green Design Institute at Carnegie Mellon University (CMU 2002). These environmental footprint categories were used in conjunction with the EIO analysis for sector-level life cycle impact assessment (Blackhurst et al. 2010; Matthews et al. 2008; Williams 2004).

Several ecological footprint types, such as fishery, grazing, forestry, cropland, and carbon dioxide (CO_2) uptake land are also analyzed for each construction sector. The ecological footprint is defined as a measure of how much area of biologically productive land and water an individual, population, or activity requires to produce all the resources it consumes and to absorb the waste (Wackernagel 2009). In this analysis, ecological footprint indicators are also considered as a part of the environmental dimension of the sustainability, and these indicators have already been used as a measure of environmental sustainability in previous input–output studies (Lenzen and Murray 2001; McDonald and Patterson 2004; Wiedmann et al. 2009). The global hectare values associated with fishery, grazing, forestry, cropland, and CO_2 uptake land are obtained from the GFN and allocated to 426 U.S. sectors based on their resource consumptions and CO_2 emissions (GFN 2010a). The aforementioned environmental indicators are briefly explained as follows:

- The water footprint is a measure of direct and indirect water used by each industrial sector. The EIO-LCA model uses the United States Geological Survey (USGS) data to estimate direct water withdrawals

for each consumption category such as power generation, irrigation, industrial, livestock and aquaculture, mining, public supply, and domestic water use. Some of these USGS categories are then allocated to different industrial sectors that are in the U.S. economic input–output table (Blackhurst et al. 2010). All water footprint results are presented in terms of cubic meter.

- The carbon footprint is a measure of the total amount of carbon dioxide, nitrogen oxides, and methane emissions from fossil fuel combustion. In this analysis, carbon footprint calculations are based on different scopes which are set by the World Resources Institute (WRI) and the World Business Council for Sustainable Development in which all possible indirect emissions from a construction sector are considered (WRI 2004). Scope 1 includes direct GHG emissions from a construction sector, including on-site emissions from natural gas, oil, and diesel combustion. Scope 2 GHG emissions account for indirect emissions from the generation of electricity used by each construction sector (Wood and Dey 2009). Finally, Scope 3 emissions are all indirect emissions (not included in Scope 2) that occur in the value chain of the construction sectors, including all upstream emissions. All scope-based carbon footprint results are presented in terms of metric tons of CO_2 equivalents.
- The energy footprint of each sector is calculated by summing the energy content of different fossil fuels and electricity from non-fossil sources. The consumption values of major fuels by industrial sectors are obtained from the using the U.S. input–output tables (Joshi 2000). The quantities of fuel consumptions are based on the average producer price of individual fuels and are presented in terms of tera-joules.
- The cropland footprint represents the most bioproductive of all the land use types and includes areas used to produce food and fiber for human consumption, feed for livestock, crops, and rubber (GFN 2010b). The National Footprint Accounts calculate the cropland footprint according to the production quantities of 164 different crop categories. The total ecological footprint of cropland use (1.08 global hectares (gha) per capita) is allocated to the U.S. agricultural sectors completely.
- The grazing land footprint is calculated by comparing the amount of livestock feed available in a country with the amount of feed required for the livestock produced in that year, with the remainder of feed demand assumed to come from grazing land (GFN 2010b). The total ecological footprint of grazing use (0.14 gha per capita) is allocated to the U.S. agricultural sectors.
- The forestland footprint is calculated based on the amount of lumber, pulp, timber products, and fuel wood consumed by a country on a yearly basis (GFN 2010b). The total ecological footprint of forest use (1.03 gha per capita) is allocated to the U.S. forestry nurseries, forest products, and timber tracks sector.
- The fishery land footprint, in other words, fishing grounds footprint is calculated using estimates of the maximum sustainable catch for a variety of fish species. The calculation is based on the estimated primary production required to support the fish caught (GFN 2010b). Assigned completely to the U.S. fishing sector is the total ecological footprint of fishing ground (0.10 gha per capita).
- The CO_2 uptake land is calculated as the amount of forestland required to absorb given carbon emissions (GFN 2010b). CO_2 emissions, generated primarily from the fossil fuel combustion, account for the largest portion of nation's ecological footprint. The total CO_2 emissions related to fuel consumption of industrial sectors, transportation, households, and government are obtained from the U.S. Energy Information Administration (EIA 2010). Then, the total ecological footprint for CO_2 uptake (4.79 gha per capita) is allocated to the U.S. sectors based on their CO_2 emissions.

4 Construction sectors and sustainability assessment

The economic output values of each U.S. construction sector were obtained from the U.S. Department of Commerce input–output tables (BEA 2002). Table 1 lists seven different construction sectors along with their acronyms and 2002 industry outputs. Among the U.S. construction sector, "Non-residential Commercial and Health Care Structures" (NR-CHCS) consists primarily of different structures such as office building, educational building, airport building, industrial warehouse, hospital, hotel, etc. "Non-residential Manufacturing Structures" (NR-MS) includes manufacturing plants such as cement, aluminum, chemical, incinerator, etc., and "Other Non-residential Structures" (NR-OTR) compromises of heavy civil infrastructures including highway, bridge, dams, water, sewer, petroleum, gas, power, and communication lines. In addition, residential construction sectors include the "Residential Permanent Single and Multi-Family Structures" (R-PSMFS), and "Other Residential Structures" (R-OTR), and maintenance and repair works are represented by the sectors of "Non-Residential Maintenance and Repair" (NR-MR) and "Residential Maintenance and Repair" (R-MR), respectively.

The developed EIO-based sustainability assessment model was used to identify the environmental, economic, and social impacts of previously mentioned construction sectors in a holistic way. To achieve this goal, the results are presented using two different metrics, such as "multiplier"

Table 1 U.S. construction sectors and total economic outputs ($M)

Sector acronym	Description	Total industry output ($M)
NR-CHCS	Non-residential Commercial and Health Care Structures	129,239
NR-MS	Non-residential Manufacturing Structures	23,465
NR-OTR	Other Non-residential Structures	292,328
R-PSMFS	Residential Permanent Site single and Multi Family Structures	304,950
R-OTR	Other Residential Structures	133,483
NR-MR	Non-residential Maintenance and Repair	101,516
R-MR	Residential Maintenance and Repair	47,379

and "total impact." First, multiplier incorporates direct plus indirect sustainability effects (e.g., water footprint, income, tax) per $M output of each construction sector. Second, total impact is the product of multiplier and total economic output of construction sector for each sustainability indicator.

4.1 Economic impacts

4.1.1 GOS

When we look more closely at GOS multiplier, which is defined as total GOS per $M economic output, R-MR shows the highest values compared with others. This result also indicates that residential maintenance and repair work requires more capital outlay than new construction. In addition, residential construction sectors are found to have higher GOS multiplier than non-residential construction sectors. R-MR sector is then followed by R-OTR and R-PSFMS in terms of GOS multiplier. The on-site construction activities contribute highly on total GOS multipliers for these residential sectors, as well.

For non-residential sectors, indirect suppliers, including L2, L3, and higher are responsible for over 60 % of total GOS (Fig. 1a). For total GOS, R-PSFMS and NR-OTR show the highest values in comparison with other construction sectors (see Fig. 1b).

4.1.2 GDP

In addition to GOS, the direct and indirect contributions of each construction sector to GDP is also investigated. The analysis results reveal that GDP multiplier is the same for all construction sectors. This is because this multiplier represents the dual of the input–output equation which simply gives the unit price. The contribution of on-site construction activities (represented by L1) to GDP has the higher percentage values for non-residential sectors compared with residential ones. On the other hand, the indirect suppliers are responsible for approximately 60 % of total GDP generated by per $M output of U.S. residential sectors (see Fig. 1c). In parallel with total economic outputs, R-PSFMS and NR-OTR represent the construction sectors with the highest contribution to GDP (see Fig. 1d).

4.1.3 Import

The import analysis results show that NR-MS has the highest import multiplier in comparison with other construction sectors. L2 suppliers of this sector are responsible for more than 60 % of total imports (see Fig. 1e). This sector is followed by R-PSFMS and R-MR, respectively. For the remaining construction sectors, L2 suppliers contributed to approximately 40 % of total import, and the rest is found in the higher-order suppliers. On the other hand, there is no direct import related to construction sectors. For total import generated by each sector, R-PSMFS and NR-OTR show the highest values in comparison with others sectors (see Fig. 1f).

A further analysis is also conducted to gain valuable insights regarding the imports of metallic and non-metallic minerals since construction is the largest consumer of these raw materials in U.S. by weight (Horvath 2004). In the U.S. input–output tables, the metallic and non-metallic minerals, which are highly utilized in construction, are represented by the sectors of "Iron Ore Mining (IO-M)," "Copper, Nickel, Lead and Zinc Mining (CNLZ-M)," "Stone Mining and Quarrying (S-MQ)," "Sand, Gravel, Clay and Ceramic and Refractory Minerals Mining and Quarrying (SGCCR-MQ)," and "Other Non-metallic Mineral Mining and Quarrying (ONMM-MQ)," respectively.

Figure 2a presents total economic output (TEO) (excluding imports), as well as overall imports related to direct and indirect consumption of metallic and non-metallic minerals based on per $M output of each construction sector. Analysis results indicate that imported minerals have the lowest economic share, and the highest percentage of minerals consumed by construction sectors is produced domestically. To illustrate, for NR-CHCS and NR-MS, TEO (excluding imports) related to production of these raw materials are found to be over 80 %, and the rest is imported from other countries. Among the construction sectors, residential constructions have the highest import of mineral products, whereas non-residential constructions which show the highest TEO are found to have the minimum total import of metallic and non-metallic minerals. In addition, NR-CHCS show more imports of metallic minerals, such as iron or copper than other construction sectors, whereas the highest share of total imports are

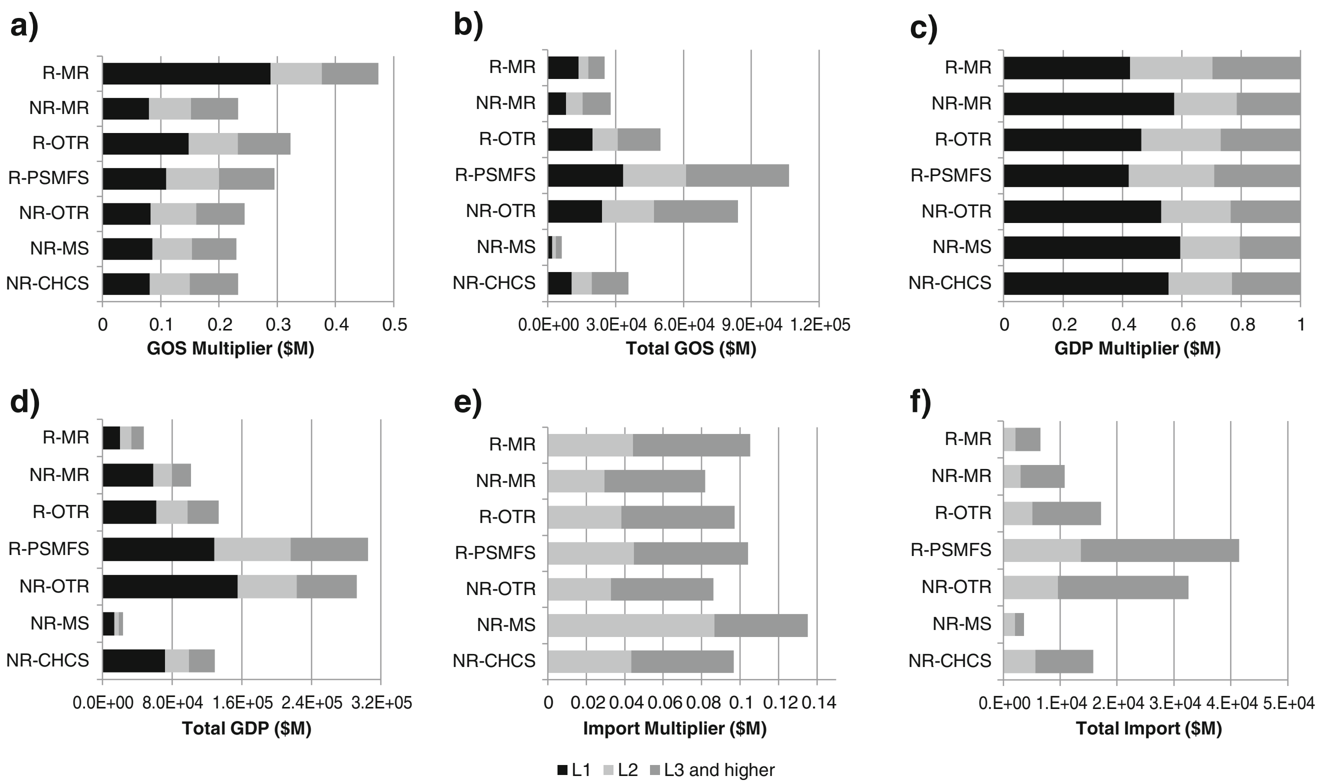

Fig. 1 Economic impacts **a** GOS multiplier ($M), **b** total GOS ($M), **c** GDP multiplier, **d** total GDP ($M), **e** import multiplier ($M), **f** total import ($M)

attributed to non-metallic minerals consumption for residential buildings, as shown in Fig 2b.

4.2 Social impacts

4.2.1 Income

Presented in this section are the income results. Based on study findings, R-PSMFS and NR-OTR have the highest value of income multiplier compared with other construction sectors (Fig. 3a). In general, non-residential construction sectors have higher income multiplier than residential sectors. Two non-residential construction sectors, such as NR-MS and NR-MR, have the largest income multiplier in comparison with other sectors. Additionally, for all non-residential U.S. construction sectors, approximately 60 % of total income is generated directly, which is represented by L1. On the contrary, direct employment impacts are found to be less than 50 % of total income for U.S. residential sectors. Among the upstream suppliers, service sectors, including “Retail Trade,” “Wholesale Trade,” “Management of Companies and Enterprises,” “Employment services,” and “Architectural, Engineering and Related Services” provide the highest contributions to total income generated by each residential sector. When analyzing the total income generated by each construction sector, R-PSMFS and NR-OTR show the highest values in comparison with others (see Fig. 3b).

4.2.2 Tax

Direct and indirect taxes generated by each sector are also investigated, and the results are presented in Fig. 3c. L2 and L3 suppliers represent 80 % of total government tax generated from each construction sector. In other words, the U.S. construction sectors generate more tax indirectly than they do directly. The results also reveal that residential construction sectors generate a higher amount of total tax per $M of their economic output in comparison with non-residential sectors, including NR-MS, NR-OTR, and NR-MR. For the residential sectors, over 90 % of total tax is generated by indirect suppliers, which are located in L2, L3, and higher layers. Among these suppliers, “Retail and Wholesale Trade,” “Real Estate,” “Electric Power Generation,” “Oil and Gas Extraction,” “Telecommunications,” and “Truck Transportation” are responsible for around 80 % of indirect tax generated in the value chain of residential sectors. When we look more closely at total government tax generated by each sector, NR-OTR and R-PSMFS represent the sectors with the highest total tax generation (see Fig. 3d).

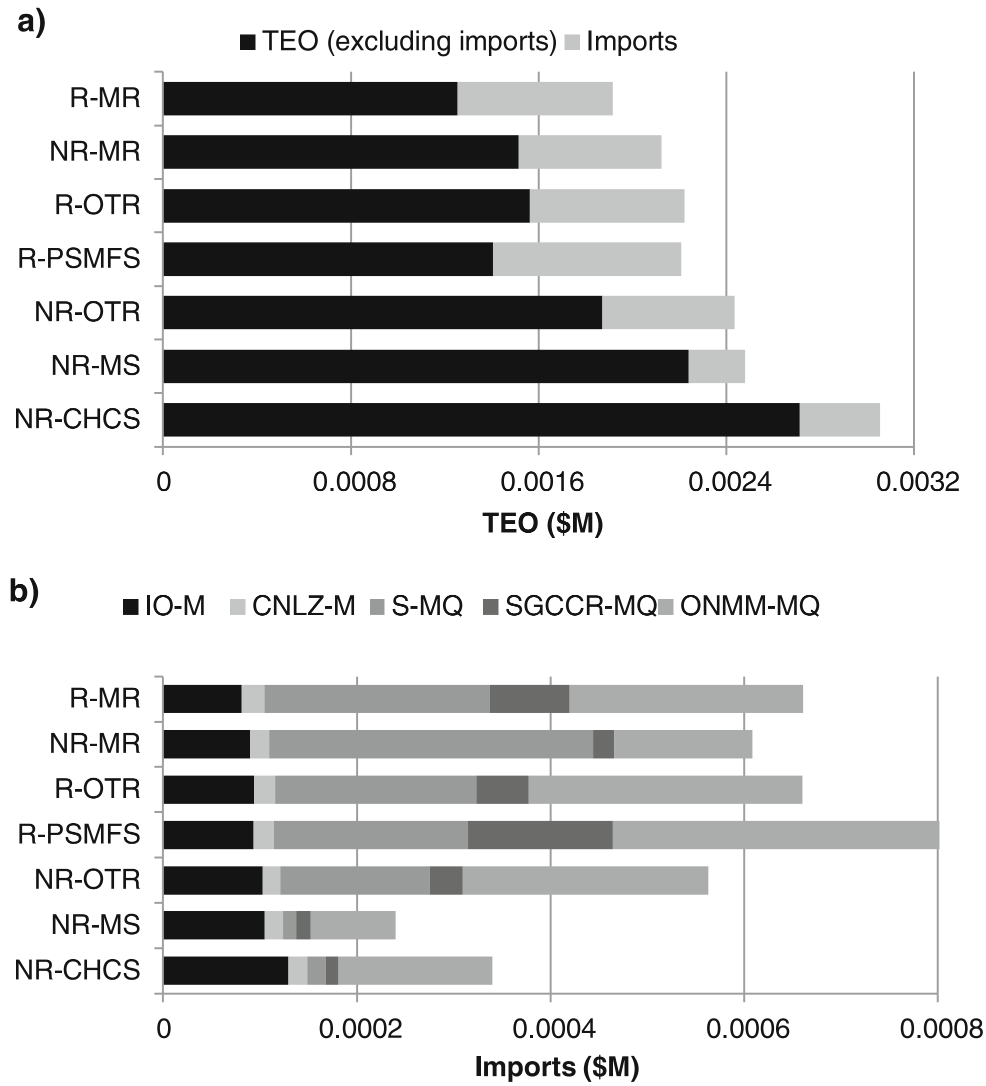

Fig. 2 Economic analysis of metallic and non-metallic mineral consumption based on per $M output of construction sectors **a** TEO ($M), **b** imports ($M)

4.2.3 Work-related injuries

In addition to income and tax, the direct and indirect contributions of each construction sector to work-related injuries is also investigated. The analysis results indicate that injury multiplier of each sector is found to be similar for non-residential construction sectors. The contribution of on-site construction activities (represented by L1) to injuries has the higher percentage values for non-residential sectors compared with all residential construction sectors. For NR-CHCS, NR-MS, and NR-MR, the on-site activities are responsible for over 60 % of total work-related non-fatal injuries (see Fig. 3e). On the contrary, it was found that residential sector have more injuries indirectly than they do directly. In addition, non-residential construction sectors are found to have higher injury multiplier in comparison with residential sectors. From the analysis results, it is apparent that R-PSFMS and NR-OTR represent the construction sectors with the highest total work-injuries among the U.S. constriction sectors (see Fig. 3f). It is should also be noted that income and injury multipliers show a similar trend and sectors with high income multiplier also have the highest total work-related injuries per $M economic output.

4.3 Environmental impacts

4.3.1 Energy footprint analysis

Presented in this section are the total energy footprint results. Initially calculated were the energy multipliers of different construction sectors. Among the construction sectors, R-MR had the highest energy multiplier compared with other sectors. Following this sector were the R-PSMFS and NR-MR, respectively (Fig. 4a). The analysis results also show that less than 40 % of total energy footprint can be attributed to direct or on-site construction activities (represented by L1) for all construction sectors. To give an example, for R-MR, about one third of total energy consumption

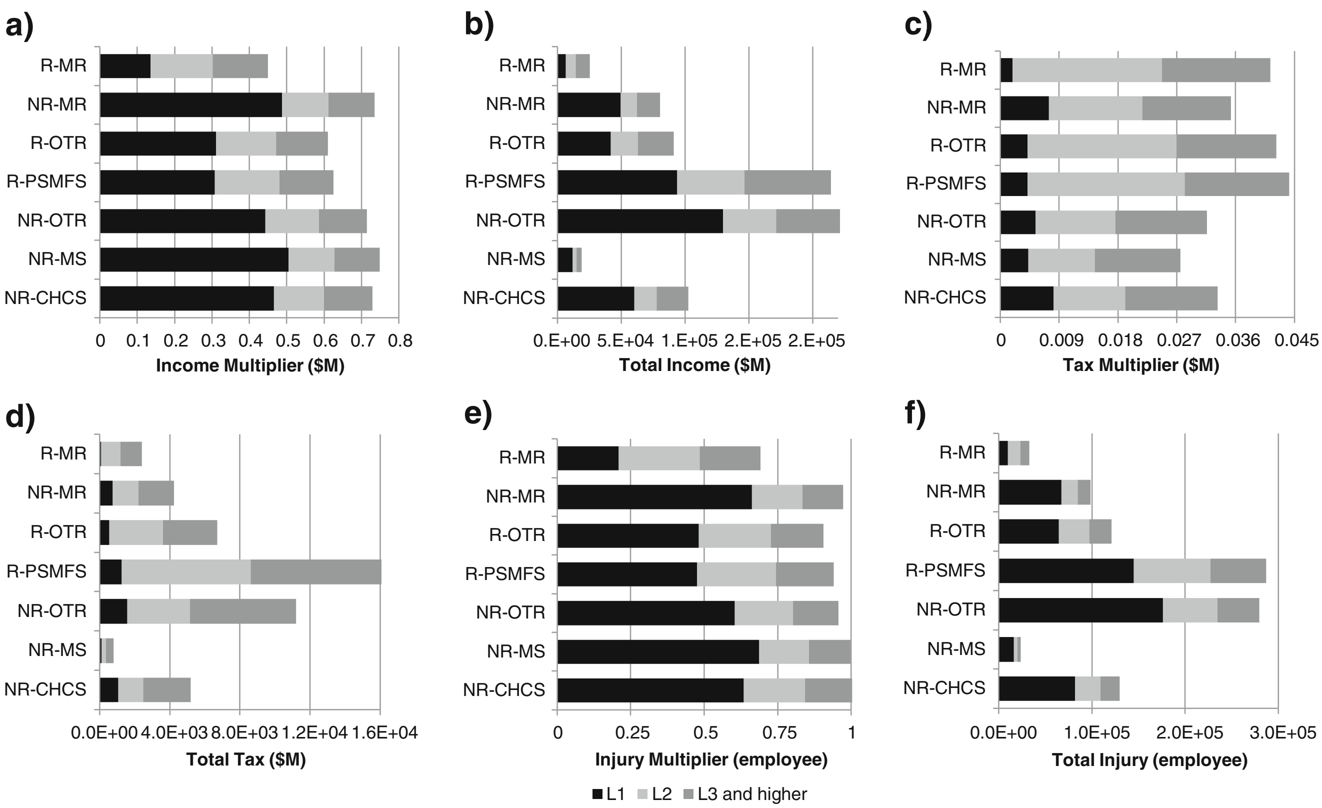

Fig. 3 Social impacts **a** income multiplier ($M), **b** total income ($M), **c** tax multiplier ($M), **d** total tax ($M), **e** injury multiplier (employee), **f** total injury (employee)

is found to be in L1, whereas two thirds (63 %) of total energy utilization can be attributed to indirect suppliers of this sector, which are located in L2, L3, and higher layers of the supply chain. For R-OTR, about 25 % of total energy consumption can be attributed to on-site construction processes, whereas 75 % of total energy use is found to be in higher order suppliers. For this reason, it should be noted that, although energy efficiency of on-site construction activities are important for residential and non-residential sectors, supply-chain-based energy consumption still has a dominant impact on overall energy footprint.

Based on total energy consumption results, R-PSMFS and NR-OTR sectors show the largest energy footprint values compared with other construction sectors (see Fig. 4b). Analysis results also show that the U.S. sectors, including "Electric Power Generation, Transmission, and Distribution," "Cement Manufacturing," "Truck transportation," "Petroleum refineries," "Iron and Steel Mills and Ferro Alloy Manufacturing," and "Oil and Gas Extraction" have the highest contributions to total energy footprint of U.S. construction industry and should be considered for more effective energy footprint reduction strategies. For example, the U.S. Green Building Council (USGBC 2009) developed a green building rating system, namely Leadership in Energy and Environmental Design (LEED). In materials and resources category of this rating system, the use of regionally produced building materials and products receives credit toward LEED certification. The findings of energy footprint analysis also support this credit strategy in order to minimize transportation distance of construction materials since truck transportation is among the top three supply sectors which have the highest share on total energy footprints.

4.3.2 Water footprint analysis

Figure 4c also presents the total water multipliers of each construction sector. First, R-MR and R-PSMFS are found to have the highest total water footprint per $M economic output. Among the construction sectors, residential constructions consume higher amounts of water than non-residential construction sectors based on per $M economic activity. In addition, for all construction sectors, on-site construction processes are found to be responsible for less than 5 % of total water consumption, whereas about 95 % of total water use can be attributed to indirect suppliers, which are located in L2, L3, and higher layers. Hence, it is important to note that construction sector uses more on-site than they do off-site. Based on total water footprint results, R-PSMFS and NR-OTR represent the construction sectors with the highest total water consumption amounts (see Fig. 4d).

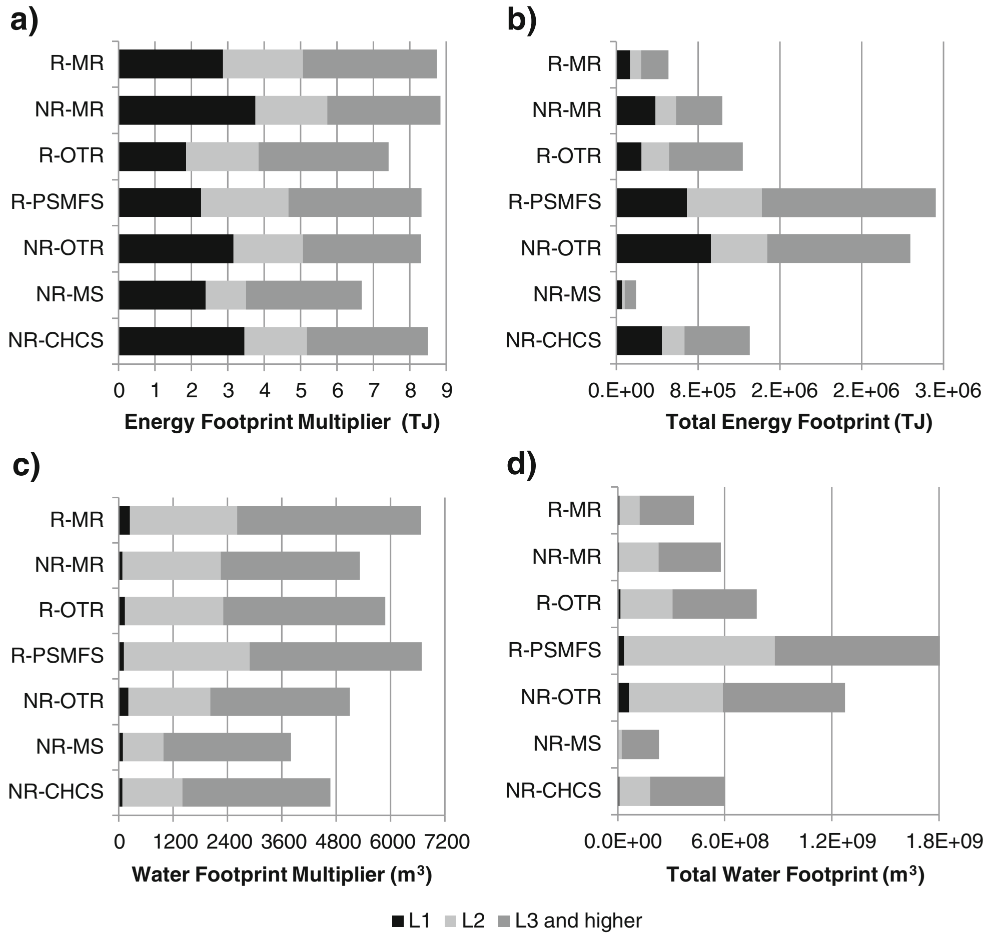

Fig. 4 Environmental impacts **a** energy footprint multiplier (tera-joules), **b** total energy footprint (tera-joules), **c** water footprint multiplier (cubic meter), **d** total water footprint (cubic meter)

When analyzing the supply chain of these two construction sectors were more closely, sectors such as, "Electric Power Generation, Transmission, and Distribution," "Paint and Coating Manufacturing," "Grain farming," and" Stone Mining and Quarrying" are found to be responsible for nearly 80 % of total supply-chain-related water consumptions. Especially, direct suppliers (represented by L2) of residential construction sectors are found to be responsible for nearly 40 % of water footprint, and the largest portion of this water consumption is attributed to electric power utilization. Therefore, any improvement in electricity consumption through increased energy efficiency or use of non-fossil renewable energy sources might have a considerable impact on minimizing the indirect water consumption.

4.3.3 Scope-based carbon footprint analysis

The EIO analysis is also able to identify the biggest carbon hot-spots across the entire supply-chain, and past studies suggest that using narrowly defined system boundaries will generally lead to significant underestimates of carbon emissions for providing products and services (Matthews et al. 2008; Huang et al. 2009b). Hence, we used the EIO analysis to account for the Scope 1, 2, and 3 carbon emissions of different construction sectors.

To have a better insight into the emissions of construction sectors, carbon footprint multiplier, which accounts for the total GHG emissions per $M output of each sector, has been firstly presented in Fig. 5a. Analysis results revealed that R-MR, R-PSMFS, and NR-MR are found to have the highest carbon footprint multipliers compared with other construction sectors. For R-MR, NR-OTR, and R-PSMFS, Scope 3 emissions are found to be over 70 % of total GHG emissions. In addition, NR-MR and NR-CHCS show the highest Scope 1 emissions due to higher fossil fuel consumption per $M economic output. For all construction sectors, Scope 2 emissions, which account for electricity production related GHG emissions, have the lowest contribution to overall carbon footprint compared with Scope 1 and 3 GHG emissions.

Another important point to be made with regard to carbon emissions is that sectors with higher total energy multiplier, such as R-MR, NR-MR, and R-PSMFS, show high total carbon footprint multipliers in respect to other sectors. This is basically due to the fact that carbon footprint calculations of construction sectors are based on the fossil fuel consumption, such as natural gas, oil, and diesel.

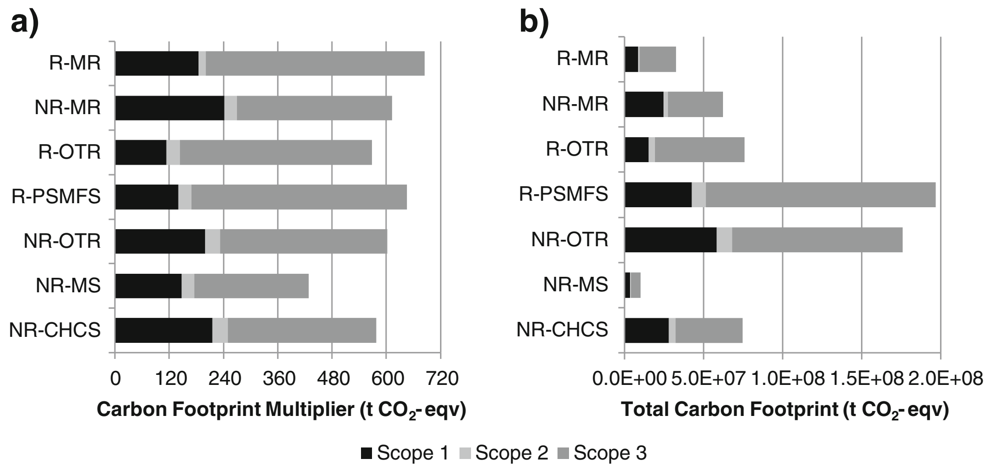

Fig. 5 Scopes 1, 2, and 3 carbon footprint analysis results; **a** carbon footprint multiplier (tons of CO_2 equivalents), **b** total carbon footprint (tons of CO_2 equivalents)

Figure 5b presents the total carbon footprint results based on different scopes. R-PSMFS have the highest amount of carbon footprint in comparison with others. This sector is followed by NR-OTR and RS-OTR, respectively. On the contrary, NR-MS and R-MR have the lowest GHG emissions compared with other construction sectors. Although the latter has the highest total carbon footprint per $M economic output, it is found to have the lowest total GHG emissions due to its low economic output.

After quantifying the total carbon footprint, it is important to account for the percentage contributions of different industrial sectors to Scope 3 carbon emissions. As can be seen from previous discussion, Scope 3 emissions are responsible for the highest GHG emissions compared with Scopes 1 and 2. It is critical to note that, although energy reduction in on-site construction activities through increased energy efficiency of building machinery or reduced electricity consumption is important, the largest portion of total carbon footprint is still found in the supply chain of these sectors. Therefore, the improvements aiming to minimize the supply-chain-related carbon footprints can make a significant impact on overall carbon emissions. When looked more closely at supply sectors, "Electric Power Generation, Transmission, and Distribution," "Iron and Steel Mills and Ferroalloy Manufacturing," "Cement Manufacturing," "Oil and Gas Extraction," "Petroleum Refineries," and "Truck Transportation" sectors are found to have the largest contributions to total Scope 3 emissions. These sectors are approximately responsible for 80 % of total Scope 3 emissions for U.S. construction sectors. To achieve a cost-effective carbon footprint reduction, the special focus might be given on these supply chain sectors to minimize the net carbon footprint.

4.3.4 Ecological footprint analysis

Presented in this section are the ecological footprint analysis results that are in the unit values of global hectares. First, ecological footprint multiplier, which presents total ecological footprints per $M output of each construction sector, have been quantified and presented in Fig. 6a. Analysis results reveal that R-MR, R-PSMFS, and R-OTR have the highest total ecological footprint multiplier in comparison with non-residential construction sectors. On the contrary, three non-residential construction sectors, such as NR-MS, NR-CHCS, and NR-OTR are found to have the lowest total ecological footprint per $M economic output. Among the ecological footprint categories, CO_2 uptake land, which is required for sequestering CO_2 emissions related to fossil fuel combustion and electricity generation, is responsible for the highest ecological footprint for all construction sectors. Followed by this are both the cropland and forestry land footprints, respectively. On the other hand, total fishery and grazing land footprints are found to be minimal when compared with other ecological footprint categories.

Figure 6b also presents the total ecological footprints of U.S. construction sectors based on their total economic outputs. The results indicate that R-PSMFS and NR-OTR are found to have the largest ecological footprints, respectively. On the contrary, NR-MS and R-MR have the lowest cumulative ecological footprint compared with other sectors. Although the latter has the highest total ecological footprint multiplier, it shows the lowest cumulative ecological footprint due to a low total economic output. In general, total forestland footprints are found to be higher for residential construction sectors. This result can be related to the higher use of wood products such as timber in building construction as opposed to heavy construction. Among the ecological footprint categories, CO_2 uptake lands represent the highest land consumption values for all residential and non-residential construction sectors. Therefore, special emphasis should be placed on reducing the total GHG emissions by considering the Scope 3 carbon footprints which have the largest share.

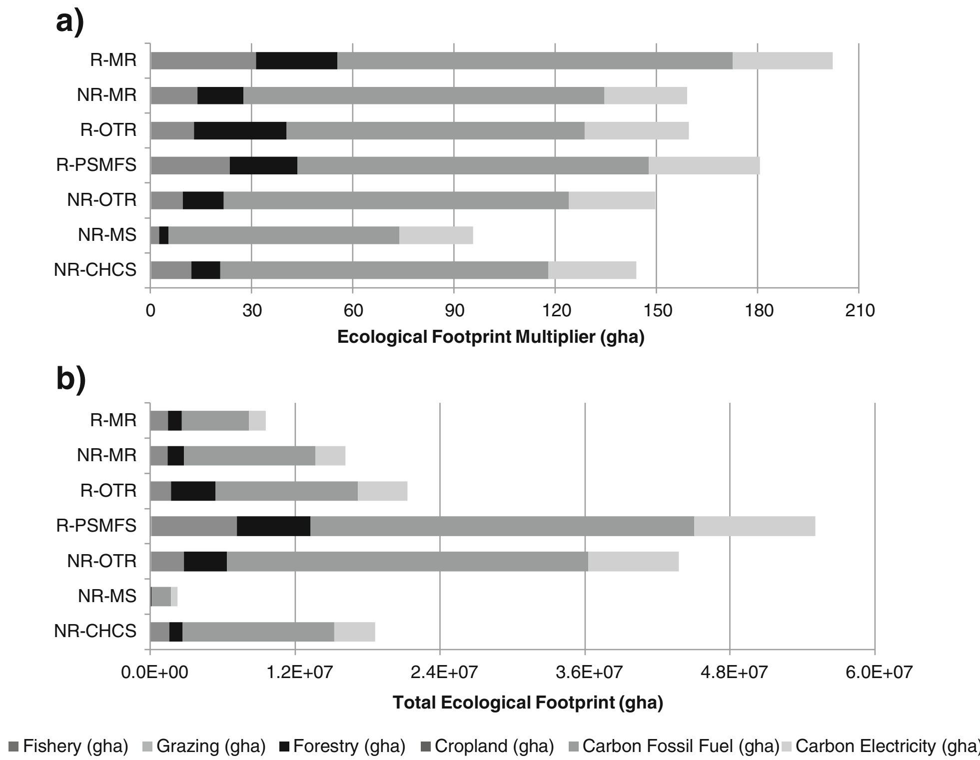

Fig. 6 Ecological footprint results; **a** ecological footprint multiplier (global hectares), **b** total ecological footprint (global hectares)

5 Conclusions

This paper analyzed the triple bottom-line sustainability implications of construction industry by proposing a distinction between seven different U.S. construction sectors. The results of such a holistic EIO analysis provide valuable insights into the location of sustainability impacts and can propose a vital guidance for decision makers to develop sound policies for sustainable construction. Especially, LEED which is a well-known and widely used building rating system in the U.S can benefit from such an analysis in order to develop effective green building rating strategies considering the construction supply chain.

The results indicate that upstream suppliers of construction sectors have the largest impacts compared with on-site activities. Hence, using narrowly defined estimation models by neglecting supply-chain-related impacts can result in large underestimates of triple bottom-line sustainability impacts of the U.S. construction industry. The findings of our research also show that NR-OTR and R-PSMFS are found to have the largest total sustainability impacts for all sustainability impact categories. Scope 3 carbon emissions are responsible for the highest share of total GHG emissions for all construction sectors. In addition, it is seen that approximately 95 % of total water use of construction sectors can be attributed to indirect suppliers, which are located in L2, L3, and higher layers. In terms of work-related injuries, non-residential construction sectors present higher injury multiplier in comparison with residential construction sector, and on-site construction works account for over 60 % of total injuries.

In combination with relevant environmental data, EIO analysis is useful for understanding the supply-chain-related indirect environmental impacts of construction and can minimize the underestimation of environmental interventions due to narrowly defined system boundaries. However, sustainability is not only limited to the environment, and other indicators of sustainability, such as economic and social, should also be taken into consideration for a more holistic analysis. LCA studies that consider all dimensions of sustainability impacts of civil infrastructures are very limited, and the current research is a first detailed study which integrates economic and social indicators with the EIO framework as an addition to environmental indicators.

The methodology described in this paper has been used to answer the question related to sustainable construction using several key sustainability metrics. Data collection process for these metrics required a considerable time and effort, and most were obtained from publicly available data sources. In future research, we propose to extend our environmental footprint metrics to provide a more robust sustainability accounting model. As an example, the built-up land footprint, which is calculated based on the area of land used by human infrastructure, such as transportation, housing, industrial structures, and reservoirs for hydroelectric power generation, can be allocated to each construction sector. However, the lack of comprehensive data set on total land uses by each construction sector is one of the main

challenges that should be addressed in future research. Furthermore, this paper analyzed the energy, water, and carbon footprints based on the use of natural resources, including crude oil, natural gas, iron, copper, crushed stone, sand and gravel, clay, limestone, wood, etc. However, a relative contribution of these resources to ecological footprint of each construction sector is still important, and the study conducted by Tatari and Kucukvar (2012b) presents a full discussion on the ecological footprint of these resources using exergy analysis.

Although the findings of this research could be very helpful to decision makers to analyze and compare the sustainability implications of construction sectors by proposing an alternative methodology, it has several important limitations that should be taken into account for future studies. First, the analysis results are based on the U.S. national input–output accounts, and therefore, there are certain uncertainties in data due to regional variations. For example, Scope 2 carbon footprints can vary from state to state or region to region depending upon electricity generation from mixes, including coal, natural gas, oil, nuclear, hydro power, solar, and other sources. Hence, these types of geographic variations in emissions should be considered for future carbon footprint estimations using the U.S. regional input–output analysis framework.

It is also important to note that the environmental interventions related to construction phase and different end-of-life scenarios are not well accounted in pure EIO analysis, and hybrid LCA model which combines the P-LCA and EIO-LCA can provide more specific and detailed life cycle sustainability analysis of construction work, particularly for construction, demolition, and waste disposal. Moreover, this current study mainly used the EIO methodology, which is based upon national input–output data that generates aggregation problems. Although economy-wide comprehensive EIO model is developed, there are still important uncertainties embedded in our results due to the use of aggregate data for construction sectors. For instance, heavy civil infrastructures, including highway, bridge, dams, water treatment facilities, sewer systems, petroleum, gas and power plants, and communication lines are analyzed the under the construction sector of NR-OTR. For more detailed life cycle sustainability assessment model, these construction sectors could be disaggregated and analyzed under NR-OTR as separate sub-sectors.

Last but not least, the sustainability impacts of imported materials used by U.S. sectors are assumed to be produced with domestic technology even though they are imported from other countries. To have a trade-linked EIO model, multi-regional input–output models can be developed in order to account for the impacts of international trade in a way that sustainability analysis results will account for the technological differences related to production of imported materials. An importance of applying multi-region input–output frameworks in input–output analysis can be found in the literature (Lenzen et al. 2004; Hertwich and Peters 2009).

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